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Spatial Characterization of MAC, a High-Resolution Optical Earth Observation Camera for Small Satellites

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Spatial calibrations have been performed on the Medium-sized Aperture Camera (MAC) of the RazakSAT satellite. Topics discussed in this paper include the measurements of system modulation transfer function (MTF), relative pixel line-of-sight (LOS), and end-to-end imaging tests. The MTF measurements were made by capturing the scanned knife-edge image on a pixel, and an issue in the MTF calculation algorithm is discussed. The method used to place the focal plane at the correct focal position is described, since they make use of MTF measurements. Relative LOS measurements are done by theodolite measurements of the telescope. Qualitative ground test result of end-to-end imaging is given.

OCIS codes : 350.6090, 110.4100, 220.1140, 350.4800

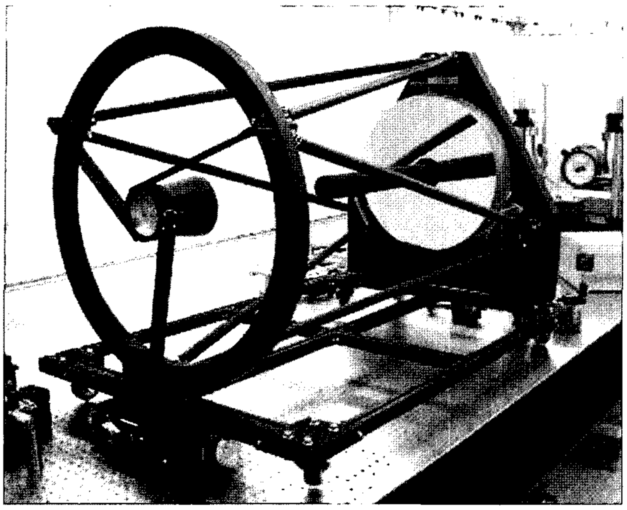
I. INTRODUCTION

Different models of the Medium-sized Aperture Camera (MAC), the primary Earth observation payload for the RazakSAT satellite, have been co-developed by Satrec Initiative and Astronautic Technology (ATSB) at different R&D stages [1-3]. The preflight radiometric and spatial characterizations have now been completed. This paper describes the spatial characterizations of the camera covering the measurement setup and equipment, modulation transfer function measurements, focal plane assembly (FPA) adjustment, pixel line-of-sight measurements, and end-to-end imaging test. The spatial characterization results are discussed.

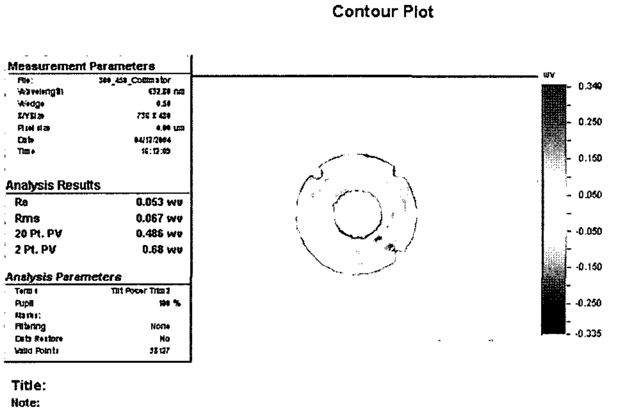
II. MEASUREMENT SETUP AND EQUIPMENT

All measurements have been done in the 10000 class optics lab in Satrec Initiative. The temperature was kept at 15+/−1℃ and the humidity was controlled at 60+/−10%. All the measurements were done on a 7 m pneumatic optical table inside a tent to minimize air turbulence.

All of the spatial characterizations employed an imaging collimator. An off-axis paraboloid collimator was used initially but was later replaced by a Cassegrain collimator due to the long focal length (4 m) of the off-axis paraboloid. A Cassegrain collimator with more compact but longer focal length (7.5 m) design occupied less space on the optical table, and the air disturbance between the collimator and MAC was reduced. The 450 mm diameter Cassegrain collimator was co-developed with Korea Research Institute of Standards and Science (KRISS), which is well described in [4]. KRISS supplied the high quality aspheric mirrors of 1/24 wv (at 632.8 nm) root-mean-square wavefront error (RMS WFE), and the opto-mechanics design and assembly were done in Satrec Initiative. Fig. 1 shows the picture of the 450 mm collimator and the diffraction-limited (0.067 wv at 632.8 nm) collimator RMS WFE interferometrically taken after the alignment and assembly. The collimator aperture should be at least the size of the camera aperture under



(a) Assembled 450 mm collimator



Measurement Parameters

File:	300_450_Collimator
Wavelength:	632.80 nm
Wedge:	0.50
X/Y Size:	736 X 480
Pixel size:	0.00 um
Date:	04/12/2004
Time:	16:12:30

Analysis Results

Ra	0.053 wv
Rms	0.067 wv
20 Pt. PV	0.486 wv
2 Pt. PV	0.68 wv

Analysis Parameters

Terms:	Tilt Power Trim2
Pupil:	100 %
Masks:	
Filtering	None
Data Restore	No
Valid Points	38127

Title:
Note:

(b) Diffraction-limited collimator RMS WFE

FIG. 1. Φ 450 mm collimator used for spatial characterization and the assembled collimator performance.

test, which is 300 mm for MAC. The focal length of the collimator should be longer than that of the camera under test. By making a reducing optical system, we can minimize the focus error and vibration effect at the focus of the collimator during the knife-edge scanning for system MTF tests. In the case of the 450 mm collimator, the focal length was more than three times longer than that of MAC.

III. MAC SYSTEM MTF MEASUREMENT

One of the most significant spatial characteristics for a space Earth observation camera is the MTF profile. (Particularly, the MTF at the Nyquist frequency of the charge-coupled device (CCD) is a key index of interest for spatial performance.) The MTF of the telescope can be simply measured interferometrically by autocorrelating the wavefront error, but a more demanding method should be used to measure the system MTF. The system MTF of an electro-optical camera is cascaded MTF including the MTF degradations by the detector and signal processing electronics as shown below. a

$$MTF_{Telescope} \times MTF_{Detector} \times MTF_{Signal\_elec} = MTF_{System}$$

Once the camera is operating in space, the system MTF can be measured by imaging a high-contrast edge [5] or a reflecting point target on the ground. Before it is launched, a knife-edge scanning method [6] is commonly used with the camera in the optics lab (or ideally in a thermal vacuum chamber) as it can obtain a detailed edge-spread function (ESF) with the resolu-tion smaller than the size of the CCD pixel.

The knife-edge scanning system MTF measurement scheme is described in Fig. 2 A 600W quartz tungsten halogen light source was used as the light source, and the image (or shadow) of the knife-edge was captured with the CCD at the MAC focal plane. The knife-edge was scanned by two-axis actuators and a motor driver. Through a signal processing unit, the CCD signal was fed into MACVIEWER, the data receiving and knife-edge controlling software developed in-house. The screen-shot of MACVIEWER capturing an ESF is shown in Fig. 3.

Once the ESF is obtained, it can be differentiated and Fourier transformed to obtain the MTF profile. However, when the ESF signal has noise due to the vibration while scanning the knife-edge, or due to air

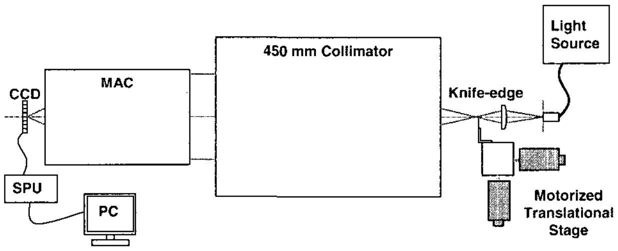
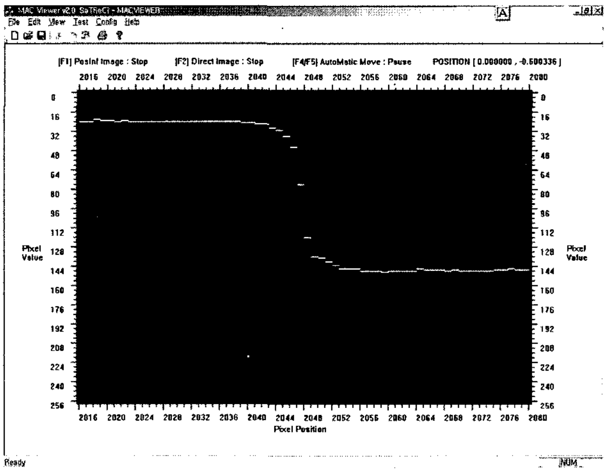
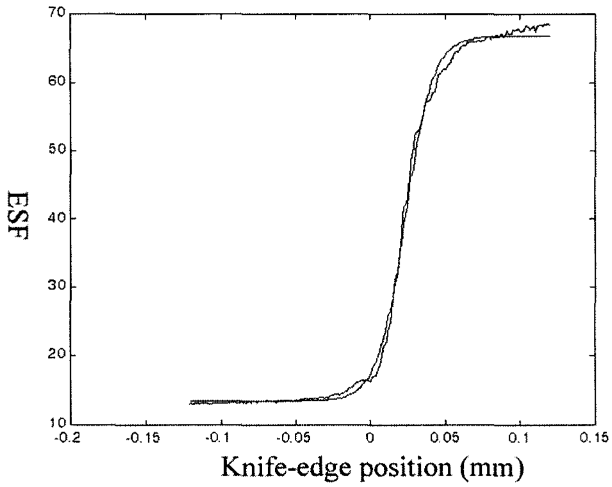


FIG. 2. System MTF measurement setup using knife-edge scanning method.

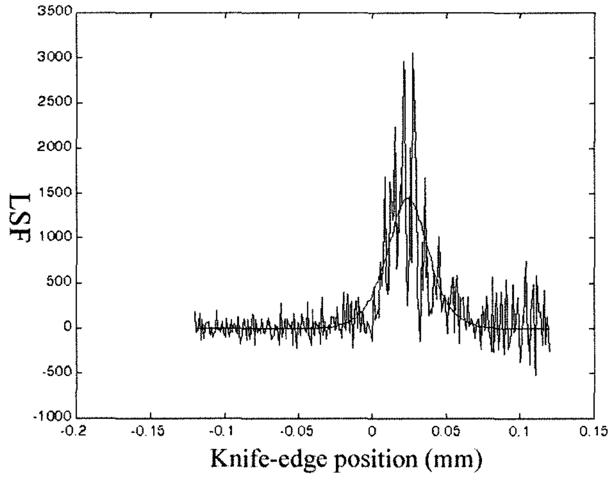


[F1] PosInf Image : Stop [F2] Direct Image : Stop [F4/F5] AutoMatic Move : Pause POSITION [0.000000 , -0.600336]

FIG. 3. MACVIEWER screenshot of an ESF.

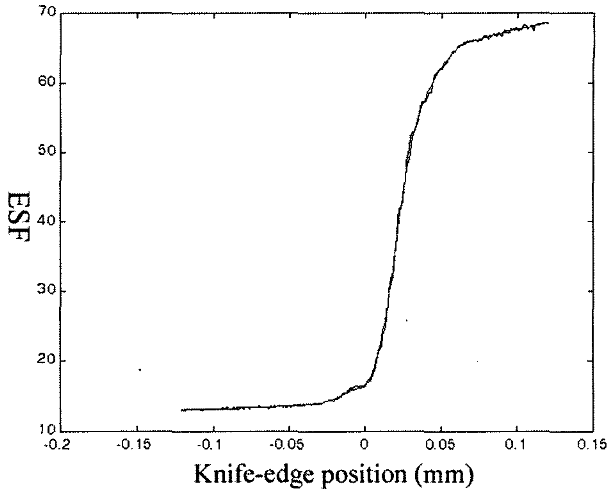


(a) Raw & fitted ESF curves.

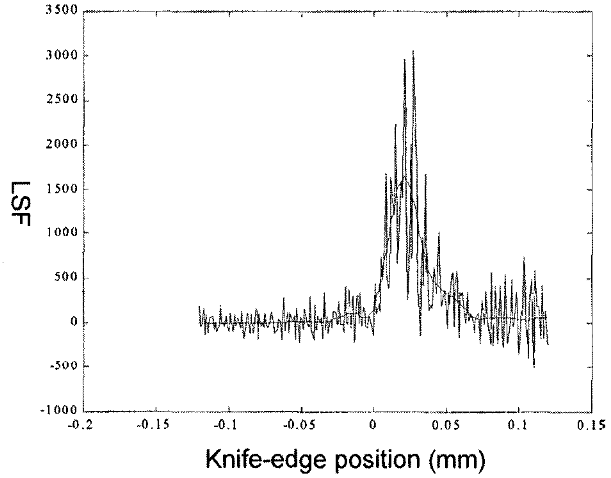


(b) LSFs from raw & fitted ESF curves

FIG. 4. LSF comparison between raw and fitted ESF curves.



(a) Raw & smoothed ESF curves.



(b) LSFs from raw & smoothed ESFs

FIG. 5. LSF comparison between raw and smoothed ESF curves.

turbulence, the noise is drastically amplified as spikes in the line-spread function (LSF). This leads to an oscillating MTF profile when Fourier transformed, giving an unreliable MTF value at higher frequency.

In order to obtain a sensible MTF profile, the ESF noise had to be reduced while maintaining the overall profile. Firstly, a fitting method was tried with a hyperbolic tangential function, but the MTF profile gave impractically low MTF values at higher frequency. Fig. 4 (a) shows a typical noisy ESF profile measured at a single pixel with the fitted sigmoid curve. Fig. 4 (b) shows the spiky LSF differentiated from the ESF and the smooth LSF differentiated from the fitted ESF. This was because the fitted ESF could not represent the folded parts of the original ESF, and consequently the LSF from the fitted ESF could not express the higher spatial frequency components. Therefore, a spline smoothing algorithm was used instead in order to reduce the noise in ESF. Fig. 5 (a) and (b) show the smoothed ESF and the consequent LSF from the same noisy ESF. The resulting MTF profile differed depending on the smoothing tolerance, and the optimum smoothing tolerance had to be found. When smoothing was excessively done, the MTF profile tends to be smaller, but when smoothing was not sufficiently done, the MTF profile oscillated.

With the established MTF measurement/calculation method, the FPA was precisely aligned. Fig. 6 shows the CCD array scheme for panchromatic (PAN) and multispectral (MS) bands. Depending on the axial position of the scanning knife-edge around the focus of the collimator, the measured MTF differed and the best MTF could be obtained at a specific axial position of the knife-edge. The best focus of the detector could be calculated by the longitudinal magnification of the collimator and MAC. Fig. 7 shows the 2-dimensional

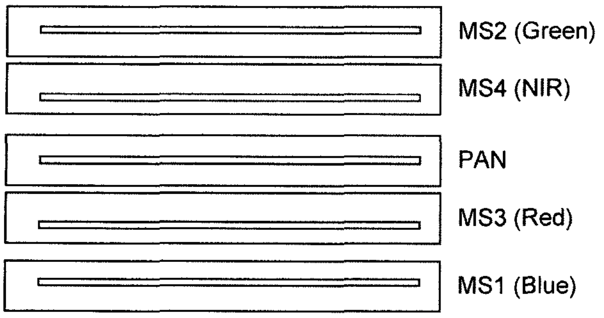


FIG. 6. CCD array scheme for FPA.

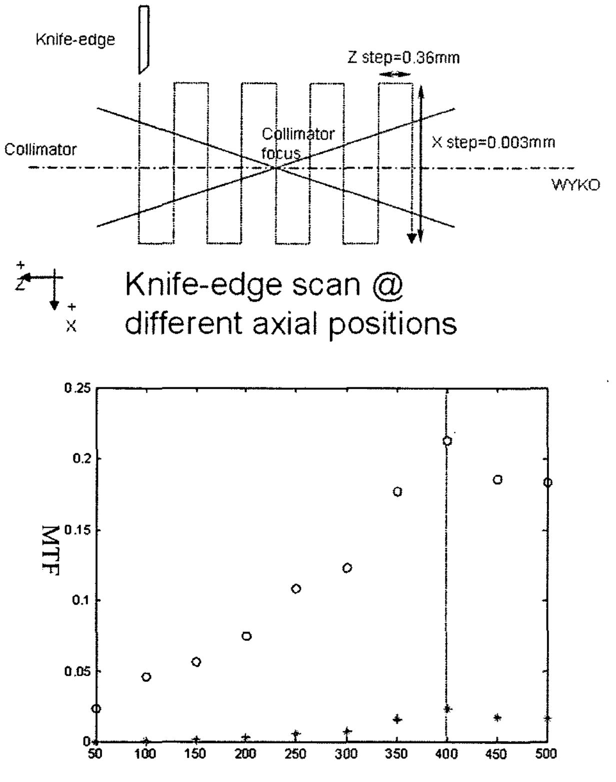


FIG. 7. Detector alignment scheme by MTF measurement.

scanning scheme and when the best CCD axial position was found. This method was iterated for the center, top, bottom, right and left of the FPA, and FPA was tilted and despaced accordingly.

Fig. 8 shows the final MTF profile of the on-axis PAN band of MAC after the flight model acoustic test. Along with the MTF profiles measured at off-axis PAN band, the preflight MTF of PAN band at the Nyquist frequency satisfied the requirement of 8%. The MTF profiles were also measured at on/off-axis points of four other MS bands, and they also met the MTF requirement of 15%.

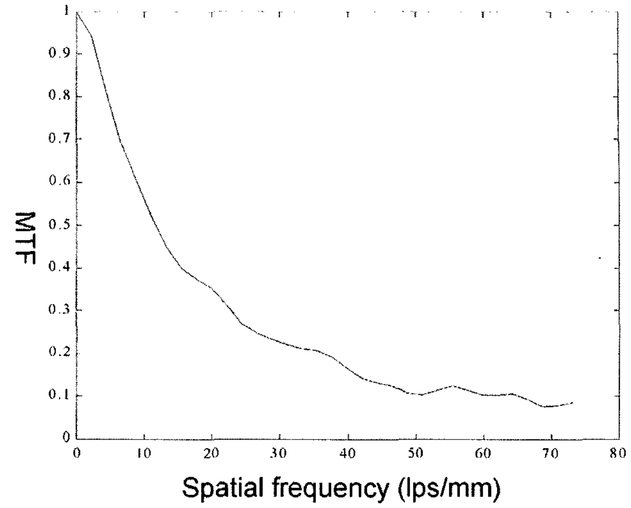


FIG. 8. Final preflight system MTF of MAC @PAN, center.

IV. MAC LOS MEASUREMENT

After the FPA alignment, relative line-of-sight (LOS) was measured for different pixels on each band. The measurement became more important for the relative pixel LOS and band-to-band registration of multispectral bands as the detector module was assembled in-house. A 100 μm pinhole was placed at the focus of the 450 mm collimator. The pinhole is approximately equivalent to a 10 m object on the 685 km orbit, and the image was captured at the CCD as a (cross-section of) point-spread function. By tilting MAC horizontally, the image of the pinhole could be pinpointed on a specific pixel. The horizontal and vertical angles were measured with a theodolite on different pixels for each band. Fig. 9 shows the statistical measurement accuracies for band-to-band registration. These are within +/−0.4 μm throughout the various pixels on MS bands, which meet the requirement of +/−0.75 pixels.

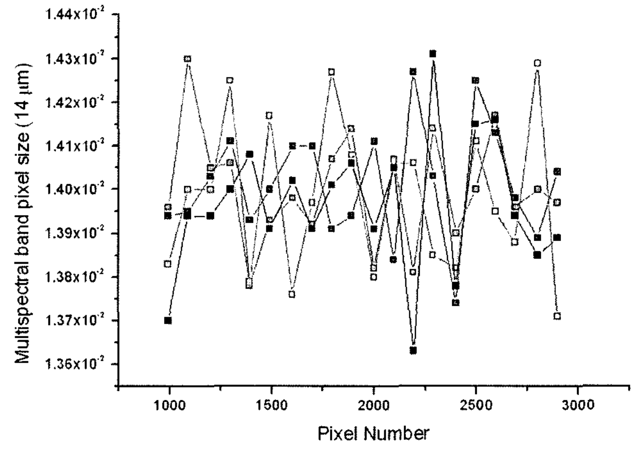


FIG. 9. Relative LOS measurement result for MS bands.

V. MAC ENG-TO-END IMAGING TEST

End-to-end imaging tests, or quick look tests, are to check the image chain. These tests were performed in order to verify qualitatively the basic operation of the focal plane system and the reconstruction software, as well as to check for pixel defects.

An illuminated transparent slide film was translated vertically with the correct speed at the focus of the collimator in order to simulate the push-broom scanning condition in space. As the field of view of the collimator was considerably smaller than that of MAC, only approximately 800 pixels were exposed simultaneously. The image in each band was reconstructed in MACVIEWER and the results were displayed. For each band, while the slide was scanned vertically, MAC was swept horizontally in order to see the pixel defects in the band, and it showed no impaired pixels. Fig. 10 shows an example of a reconstructed image at PAN channel. (The edge part is darker due to the field limitation and non-uniform illumination of the light source.) For future work, it would be ideal to use a separate collimator covering the whole field of view of the camera under test, solely for the end-to-end imaging test purpose.

VI. CONSLUSION

Various spatial characterizations of the earth observation camera MAC on RazakSAT were carried out. The camera system MTF measurement, relative LOS measurement, and end-to-end imaging tests were done, all using 450 mm diameter Cassegrain collimator. A smoothing algorithm rather than fitting was adopted to solve the MTF calculation problem. With the established system MTF measurement method, the FPA was carefully aligned. The measured MTF values at various pixel points on CCD after the alignment, assembly, and acoustic test showed the camera meets the MTF requirements on PAN and MS bands. LOS measurement data will be used for band-to-band registration for the post processing of the images taken by MAC. End-to-end imaging tests showed that there were no pixel defects after the assembly and acoustic test, and simulated images were reconstructed. The camera flight model was successfully assembled and the integrated satellite is under final tests.

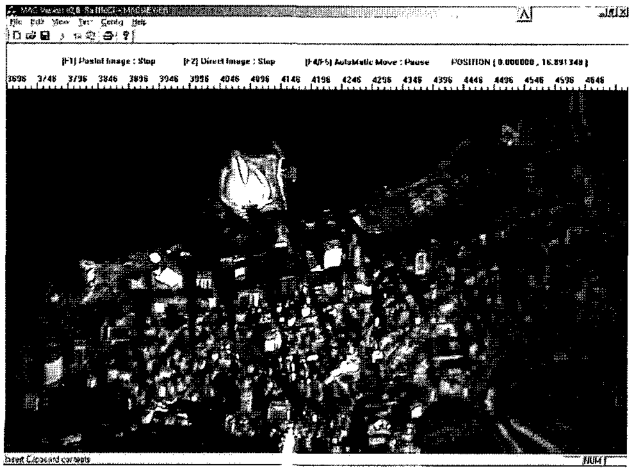


FIG. 10. An example of a reconstructed image (PAN) by end-to-end imaging test

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